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'Renewable' hydrogen: Prospects and challenges

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ABSTRACT

The increasingly manifest impacts of global warming have made it a global priority to phase out the use of petrol and diesel as transportation fuels in favour of hydrogen. But the production of hydrogen by most existing technologies entails substantial use of fossil fuels and CO_2 emissions; indeed as much as 2.5–5 tonnes of carbon is released as CO_2 per tonne of hydrogen currently produced by conventional means. Hence the production of hydrogen can be 'carbon-free' only if it is generated by employing genuinely carbon-free renewable energy sources.

The present review deals with the options, prospects, and challenges associated with this very high-priority area of global concern.

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Contents

1. Introduction

Dissociation of water by electrical or thermal means generates hydrogen and oxygen:

$$2H_2O = 2H_2 + O_2 \quad (1)$$

If this hydrogen is separated and used as a fuel, on combustion in air or oxygen it regenerates water:

$$2H_2 + O_2 = 2H_2O \quad (2)$$

If a means can be found to split water using energy produced by a renewable, 'non-carbon' source like wind or solar, the hydrogen then produced would also be a renewable source of energy in the true sense. Hydrogen can be, and is, produced on a large scale by several other processes which consume fossil fuels, for example the production of hydrogen by decarbonizing CNG, but these routes of hydrogen production are neither renewable, nor 'carbon free' [1,2]. As much as 450 billion m^3 of hydrogen is currently produced and consumed in the world (Table 1) but mostly as raw material for various other chemicals and not as a fuel [3,4]. Moreover, nearly all of this hydrogen is generated by processes which use fossil fuels, hence by 'unclean' route. For each tonne of hydrogen produced from hydrocarbons, approximately 2.5 tonnes of carbon is released as CO_2. When hydrogen is produced from coal, approximately 5 tonnes of carbon is emitted per tonne of hydrogen to the atmosphere [3,5].

Unfortunately, at the present level of advancement in different technologies for hydrogen production, the one based on water consumes the maximum energy (Fig. 1) [6]. For this reason only a small fraction of total hydrogen production in the world at present is based on water as a raw material (Fig. 2).

But there is very great thrust towards shifting from fossil-fuel based economy to an economy based on hydrogen as fuel [7–11]. As explained above, the combustion product of hydrogen being water,

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Table 1
Hydrogen consumption in the world.

Category	Hydrogen consumed	
	Billion m^3	Share (%)
Ammonia producers	273.7	61
Oil refineries	105.4	23
Methanol producers	40.5	9
Others	13.6	3
Merchant users	16.1	4
Total	449.3	100

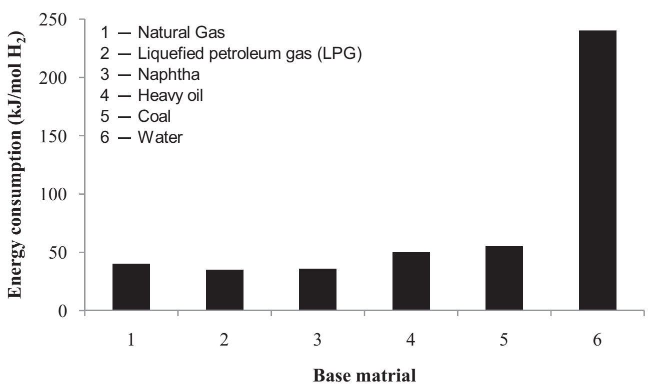


Fig. 1. Relative energy consumption in the production of hydrogen from different materials at the present level of technology

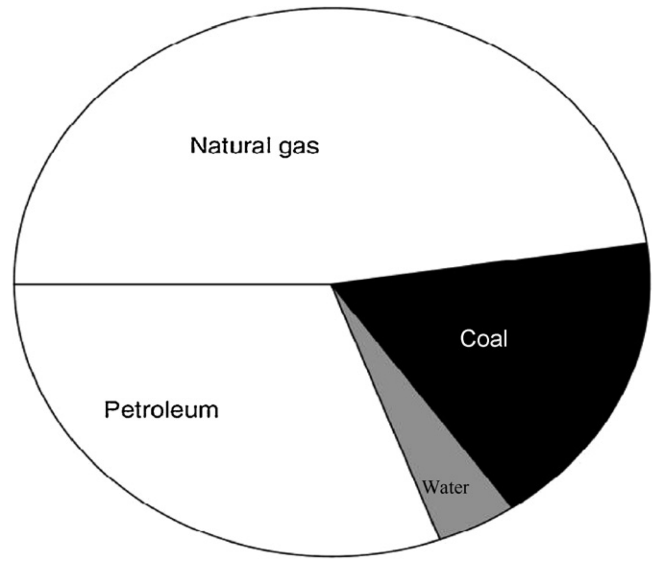


Fig. 2. Relative quantities of raw materials presently used for hydrogen production

it is a non-polluting fuel when burnt. Despite this great advantage, there are problems associated with hydrogen usage which are to be solved. For example hydrogen is the lightest of all elements (Table 2); and is much more difficult to liquefy than methane and propane (which are the constituents of LPG and CNG)—the critical temperature of hydrogen being very low (Table 2). The energy density of hydrogen is also much lower than other fuels (Table 3) which means a vehicle running on hydrogen has to have much larger fuel tank than a petrol/diesel run vehicle. Some other properties of hydrogen in comparison to other fuels are presented in Table 4.

There are also concerns over problems related to hydrogen gas leakage [12]. Due to the small size and light weight of hydrogen molecules, molecular hydrogen leaks from most containment ves-

Table 2
Some physical properties of hydrogen.

Characteristic	Value
Molecular weight	2.01594
Density of gas at 0 °C and 1 atm	0.08987 kg/m^3
Density of solid at −259 °C	858 kg/m^3
Density of liquid at −253 °C	708 kg/m^3
Melting temperature	−259 °C
Boiling temperature at 1 atm	−253 °C
Critical temperature	−240 °C
Critical pressure	12.8 atm
Critical density	31.2 kg/m^3
Heat of fusion at −259 °C	58 kJ/kg
Heat of vaporization at −253 °C	447 kJ/kg
Thermal conductivity at 25 °C	0.019 kJ/(m °C)
Viscosity at 25 °C	0.00892 centipoise
Heat capacity (Cp) of gas at 25 °C	14.3 kJ/(kg °C)
Heat capacity (Cp) of liquid at −256 °C	8.1 kJ/(kg °C)
Heat capacity (Cp) of solid at −259.8 °C	2.63 kJ/(kg °C)

Table 3
Energy densities of common fuels and hydrogen.

Fuel	Energy density (MJ/m^3 at 1 atm, 15 °C)	Energy density (MJ/m^3 at 200 atm, 15 °C)	Energy density (MJ/m^3 at 690 atm, 15 °C)	Energy density (MJ/m^3 of liquid)	Gravimetric energy density (MJ/kg)
Hydrogen	10	1825	4500	8491	140.4
Methane	32.6	6860		20,920	43.6
Propane	86.7			23,488	28.3
Gasoline				31,150	48.6
Diesel				31,435	33.8
Methanol			15,800	20.1	

Table 4
Comparison of hydrogen with other fuels.

Fuel	LHV (MJ/kg)	Stoichiometric			Flame temperature (°C)	Minimum ignition energy (MJ)	Autoignition temperature (°C)
		HHV (MJ/kg)	Air/fuel ratio	Combustible range (%)			
Methane	50	55.5	17.2	5–15	1914	0.30	540–630
Propane	45.6	50.3	15.6	2.1–9.5	1925	0.30	450
Octane	47.9	15.1	0.31	0.95–6.0	1980	0.26	415
Methanol	18.0	22.7	6.5	6.7–36.0	1870	0.14	460
Hydrogen	119.9	141.6	34.3	4.0–75.0	2207	0.017	585
Gasoline	44.5	47.3	14.6	1.3–7.1	2307	0.29	260–460
Diesel	42.5	44.8	14.5	0.6–5.5	2327		180–320

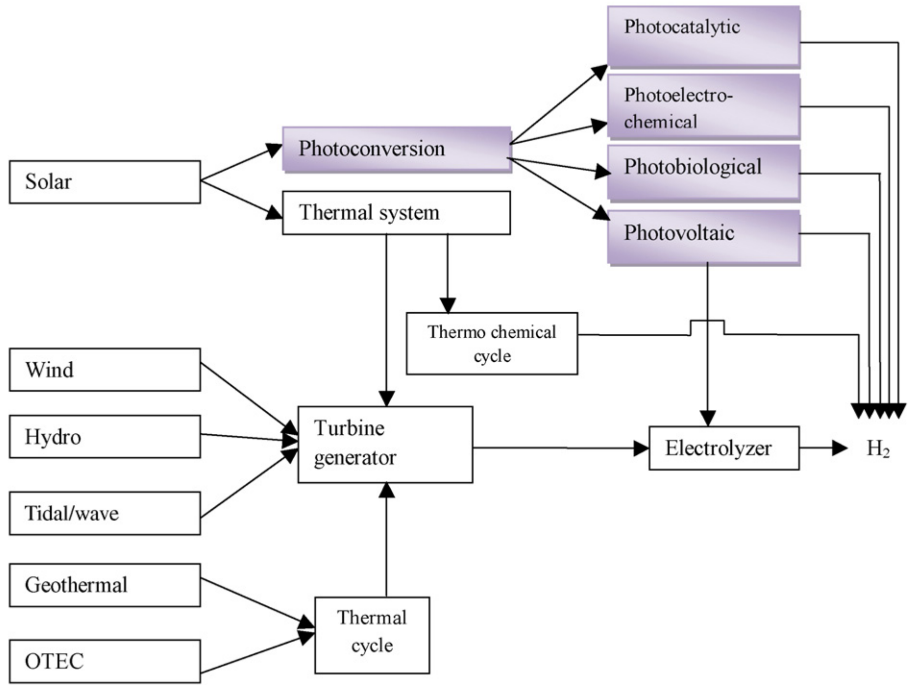


Fig. 3. Direct (shaded rectangles) and electrolytic routes to production of hydrogen using renewable energy sources.

sels. It has been hypothesized that if significant amounts of H_2 escape to the stratosphere, free radicals of hydrogen can be formed due to ultraviolet radiation, which in turn can enhance the ozone depletion [3].

2. Production of renewable non-carbogenic hydrogen

If the use of a renewable energy resource for generating hydrogen can be made economically viable it would also provide a means of storing, and utilizing at will, the energy source. For example wind and solar energies are intermitant. An excess of them is generated at certain times and there is zero generation at some other times. This makes it necessary to find a way by which energy generated from these sources is stored for use when needed. Conversion to hydrogen is one of the most desirable options [13–15].

The existing methods for the production of 'renewable' hydrogen can be divided into two major categories: direct and electrolytic conversion methods (Fig. 3). Of these, the electrolytic route is common to all the renewable non-carbogenic resources; in it the energy source is first converted to electricity followed by the production of hydrogen via electrolysis of water. When the energy source is direct solar, it can be converted to hydrogen via both electrolytic and direct conversion routes [16–18].

3. Solar hydrogen

Solar hydrogen is considered an ultimate solution to energy and environmental problems facing mankind, and, not surprisingly, it is an object of very intense research efforts worldwide [10,19–23]. As shown in Fig. 3, solar hydrogen can be produced by splitting water via:

(i) Combination of a solar cell with an electrolyzer.
(ii) Combination of a concentrated solar thermal system with a turbine and an electrolyzer.
(iii) Combination of a solar concentrating system with a thermo-chemical water-splitting cycle.
(iv) Direct photoconversion (photocatalytic, photoelectrochemical, photobiological).

Coupling of solar cell, for example photovoltaic (PV) and solar thermal systems with an electrolyzer represents a promising near-term option for solar production of hydrogen. While solar cell is a well established technology, it is still either too expensive or lacks sufficiently high energy efficiency for the widespread commercial production of hydrogen [18,24]. Assuming that water electrolysis devices operate at 70–75% energy efficiency, the total (or integrated) solar-to-hydrogen (STH) energy efficiency is only about 8–14% for commercial silicon-based PV cells [25]. It has the potential to rise to 25–30% and even higher if more advanced PV cells and electrolyzers can be developed [12,25]. Kelly et al. [10,18] report a strategy for optimizing hydrogen generation and battery charging using solar systems in which no charge controllers or power converters are needed. This reduces costs and improves systems efficiency. The PV panels are connected directly to the electrolysis unit by designing the solar collectors to provide minimum power at a voltage that would match the fixed operating voltage to the electrolysis cell [26]. A slightly different procedure is used for an optimized solar battery charging module by taking advantage of the sharp fall-off in the PV module voltage at voltages above the maximum power point (MPP), resulting in self-regulation of the battery charging.

In 1995, the first solar hydrogen facility began operations in El Segundo, California. It used an advanced PV system coupled with an electrolyzer and produced about 50–70 m^3/day of hydrogen. From then onwards a number of systems have been set up to demonstrate the feasibility of generating 'solar' hydrogen and finding ways to improve its economics. Recent efforts include a stand-alone demonstration unit in which a polymer electrolyte membrane electrolyzer system for generating hydrogen is directly energized by a PV solar array [14], and a weather station based on a PV storage [15]. As a part of the US Department of Energy's Hydrogen, Fuel Cells and Infrastructure Technologies programme, its National Renewable Energy Laboratory (NREL) is testing and characterizing

Table 5
Efficiency of the electrolyzers and stacks at the wind-to-hydrogen demonstration project at NREL, USA.

Efficiency	PEM electrolyzer		Alkaline electrolyzer	
	LHV	HHV	LHV	HHV
Stack efficiency				
Low current	80% (5 A)	95% (5 A)	78% (30 A)	92% (30 A)
Rated current	63% (5 A)	75% (135 A)	59% (220 A)	70% (220 A)
System efficiency				
Low current	0% (15 A)	0% (15 A)	0% (35 A)	0% (35 A)
Rated current	49% (135 A)	57% (135 A)	35% (220 A)	41% (220 A)

two electrolyzer technologies—namely, polymer electrolyte membrane (PEM) and alkaline electrolyzer systems (AES). Efficiencies of the two systems were calculated using experimental data from system operation, on the basis of both the higher heating value (HHV) of hydrogen (39.4 kWh/kg) and the lower heating value (LHV33.3 kWh/kg). Stack efficiency attains a peak at low current while the overall electrolyzer system efficiency is greatest when operating at rated stack current (Table 5).

There is obvious potential for hydrogen generation by PV-electrolysis systems provided the cost of a PV system is significantly reduced. One of the possible strategies is to utilize appropriate methods to orient PV modules for optimum solar capture on cloudy days [17,18]. Conventional tracking systems increase the solar energy capture on sunny days when there are no clouds, but on cloudy days such systems can actually reduce the solar energy capture. Orienting the solar modules skyward on cloudy days can improve solar energy capture by over 40% relative to modules that are oriented towards the obscured sun.

Another method to improve component efficiencies is to remove heat from the PV system, where higher temperatures reduce efficiency, and add the captured heat to the electrolyzer, where higher temperatures improve efficiency [10]. Attempts can also be made to capture compression energy in the oxygen waste stream, as well as the hydrogen stream, in a high-pressure electrolyzer [27]. These potential improvements may contribute to making solar hydrogen production more cost effective.

3.1. Solar thermal hydrogen production systems

Solar thermal systems can provide higher STH energy conversion efficiencies than solar photoconversion systems because of potentially higher solar-to-work efficiencies [1,28]. The overall STH energy conversion efficiency of a solar thermal system can be determined by multiplying the system efficiency η_s by the electrolyzer efficiency:

$$\eta_{STH} = \eta_S \eta_{el} \quad (3)$$

where η_{STH} is overall solar-to-hydrogen energy conversion efficiency; η_s is the efficiency of solar-to-work conversion, and η_{el} is an electrolyzer efficiency.

At an electrolyzer efficiency of 70–75%, the tower and dish-type concentrators with concentration ratios of 1000 and 10,000 when coupled with the electrolyzer can generate hydrogen with the STH efficiencies of 50% and 60%, respectively. Coupling of high and ultra-high temperature solar concentrators with thermochemical water splitting cycles (TWSC) can potentially offer even higher STH efficiencies (up to 60–70%) compared to photo conversion and solar concentrator–electrolyzer systems because there is no need for intermediate conversion of solar heat to electricity, and $\eta_{STH} = \eta_s$. Solar concentrating systems can achieve much higher temperatures (up to 2500 °C and even higher) compared to nuclear reactors (up to 1000 °C), which allows significant expansion of the range of thermochemical cycles that could be utilized for hydrogen production from water [3]. Solar chemical reactors coupled with high-concentration solar systems typically utilize a cavity receiver-type configuration, i.e., a well insulated enclosure with a small opening (the aperture) to let in the concentrated solar radiation [21].

In theory, solar thermal production of hydrogen can be accomplished simply using concentrated solar radiation for heating up water to its dissociation temperature followed by separation of hydrogen from the equilibrium mixture. Unfortunately, the decomposition of water does not proceed with sufficiently high yield until a temperature of about 4000 °C is achieved [6,29]. Attempts have been made to directly split water using an ultra-high temperature (up to 2230 °C) solar concentrator and a ceramic membrane for H_2–O_2 separation [30]. Although conceptually simple, the direct water-splitting method potentially faces a number of daunting technical challenges, including very low rates of conversions, durability of construction materials, gas separation problem, etc., which makes this approach unlikely to succeed on a commercial scale [24].

Hence the efforts in the solar thermochemical water-splitting field have been focused on the development of multi-step cyclic processes that can be carried out at temperatures below 2000 °C. One major class of TWSC that fits in the range of temperatures provided by tower and dish-type solar concentrators are the two-step cycles involving metal (M) oxides:

$$M_xO_y \rightarrow xM + (y/2)O_2 \,(\text{endothermic}) \quad (4)$$

$$xM + yH_2O \rightarrow M_xO_y + yH_2 \,(\text{exothermic or thermo-neutral}) \quad (5)$$

In most cases the reaction (4) is endothermic and requires high temperatures for its completion: ZnO ~ 2000 °C, MgO and Fe_2O_3 ~ 3400 °C, TiO2 ~ 3700 °C [31]. Thus, except for the dissociation of ZnO, all other oxides require temperatures unattainable in most practical solar concentrating systems. The Zn/ZnO redox reactions can be utilized via a two-step thermochemical cycle: (a) endothermic thermal dissociation of ZnO(s) into Zn(g) and O_2 at 2730 K using process heat derived from concentrated solar energy, and (b) the exothermic hydrolysis of Zn(I) at 700 K to from H_2 and ZnO(s) [32,33].

There are several technical challenges to the Zn/ZnO redox pair that would require further R&D efforts [33,34]. Due to the high temperature of the reaction, decomposition of ZnO results in vaporization of the product Zn. It becomes necessary to quench the product, Zn, in order to avoid its reoxidation, which is difficult to accomplish in a large-scale system. Moreover, in a closed, directly heated solar reactor/receiver system, it would be problematic to prevent condensation of zinc on the optical window.

The advantages of a cycle increase as the required peak temperatures are reduced, in that a greater range of heat sources can then be considered for a given application. Consequently, research has been carried out to lower the peak temperatures required in TWSCs [35]. The use of mixed oxides, e.g., $(Fe_{1-x}M_x)_3O_4$ (where M = Mn, Co, Ni, Zn, Mg, etc.), Ni–Mn–Fe–O_x, etc., allows lowering of the maximum temperature of the cycle. Yet, some of the cycles have shown problems with sintering and deactivation of the metal oxides at high temperatures [36]. Besides, these cycles require handling of a very large mass of materials per unit of hydrogen produced. There have been attempts to use concentrated solar radiation to drive TWSC that were originally designed for the nuclear interface, e.g., SI cycle, and UT-3 cycle [37], with the efficiencies of 45 and 49.5%, respectively. Out of a large number of water-splitting cycles potentially suitable for the concentrated solar energy applications, 30 cycles (mostly two- and three-step cycles) operating in the temperature range of 900–2000 °C appear suitable for further evaluation [38]. A process for hydrogen production at temperatures below 550 °C, including thermochemical cycles, has been reported [35]. But rigorous experimental evaluation of the kinetics, and careful assessment

of side reactions, etc., will have to be performed before any of these can be tried on a pilot scale.

An acceptable process cycle should have these attributes:

(1) Within the temperatures considered, the change in free energy of the individual reactions should approach zero.
(2) The number of steps should be minimal.
(3) Each individual step must have both fast reaction rates and rates which are similar to the other steps in the process (so that any one step does not slow down the entire process).
(4) The reaction products should not result in chemical by-products, and any separation of the reaction products must be minimal in terms of cost and energy consumption.
(5) Intermediate products must be such that they are easily handled.

There are several processes which meet the five criteria, such as the Ispra-Mark UT-3 process, and the sulfuric acid decomposition process [31,39]; however, they are still much costlier in comparison to other hydrogen generation technologies. In addition, these processes require large quantities of highly hazardous (toxic and corrosive) materials. The conditions of high temperatures, high pressures, and hazardous material handling also generate the need for special materials to build the reactors [40]. Finally, several of them such as the hybrid sulfur Ispra-Mark 11 process require inefficient electrochemical steps which need to be improved.

It is believed that scaling up the processes may lead to improved thermal efficiency overcoming one of the principle challenges faced by this technology. In addition, a better understanding of the relationship between capital costs, thermodynamic losses, and process thermal efficiency may lead to decreased hydrogen production costs. The current processes all use four or more reactions, and it is believed that an efficient two reaction process may make this technology viable [31]. Ewan and Allen [41] have assessed the limiting thermodynamic efficiencies of thermochemical cycles for hydrogen production on the basis of thermodynamic principles. The limiting values are instructive for designers, as they identify ideal limits and thus help realistic efficiently targets to be established. Considerations of the second law of thermodynamics are essential to determining peak efficiencies, and exergy methods can be employed in such computations. All said and done, whether the technology will also be 'clean' is a big question.

3.2. 'Solar-specific' water-splitting

It is possible to develop 'solar-specific' water-splitting cycles. This has aroused great interest because, in contrast to traditional solar-driven TWSCs that utilize only the thermal component of solar radiation (i.e., solar heat), 'solar specific' cycles also take advantage of the photonic component of the solar source, which might reduce the maximum temperature of the cycle and potentially increase overall STH energy efficiency. The approach is based on splitting water using multi-step cycles that include at least one photochemical step utilizing solar photons. One example is a hybrid sulfur ammonia (SA) photo-thermochemical water-splitting cycle developed at the Florida Solar Energy Center [42]. In this cycle, the photonic (near UV and visible photons) component of the solar spectrum is utilized for the production of H_2 and the thermal component for generating oxygen. Utilization of the full solar spectrum potentially allows this cycle to achieve higher overall efficiency than the purely thermochemical water-splitting cycles.

The intermittent nature of solar radiation availability poses problems in this route also. In contrast to nuclear-powered cycles that can operate 24 h to 7 days under any weather conditions, the solar source being of an intermittent nature, imposes severe limitations on the overall system efficiency and significantly complicates the operation of the cycles. The thermal transient conditions in the reactor–receiver and other parts of the system that are under enormous thermal stress conditions may result in failure of construction materials and, especially, of catalysts that operate efficiently in a narrow temperature range. Despite these daunting technological challenges, solar TWSCs are a very active area of solar hydrogen research, even though, as of now, no commercially viable application is in sight.

3.3. Direct solar-to-hydrogen photoconversion

Direct solar-to-hydrogen photoconversion systems (e.g., photocatalytic, photoelectrochemical, photobiological water splitting) offer certain advantages over solar thermal systems as they are less complex and operate at near-ambient conditions. Due to this reason such systems have attracted a large number of research groups worldwide since the late 1970s. The photocatalytic systems use visible light-absorbing dye- or metallo-complex-based compounds with suitable photo-redox properties to carry out splitting of water. Photoelectrochemical systems utilize low band-gap semiconductors in the form of electrodes or particulates suspended in aqueous solutions. Photobiological systems involve special algae and photosynthetic microorganisms. The direct solar photoconversion routes are based on initial absorption of solar photons, followed by a series of chemical transformations involving a photo-induced charge transfer leading to catalytic reductions of protons to molecular hydrogen and oxidation of water (or hydroxyl ions) to molecular oxygen. The down side is that even though these reactions can be conducted at low temperature (due to photo-activation of the reacting species, as opposed to thermal activation which is characteristic of thermochemical water splitting), the solar-to hydrogen efficiencies of the direct photoconversion systems are relatively low (less than 10%), and most of them lack long-term stability (they are subject to photodegradation).

In addition to semiconductor devices for photoelectrolysis, it is possible to use suspended metal complexes in solution as the photochemical catalysts. Typically, nano-particles of ZnO, Nb_2O_5 and TiO_2 have been used [43]. These systems promise the use of low cost materials and high efficiencies. Current research is devoted to realizing this promise. This application of nanotechnology offers new hope but when it will translate into a reality is hard to tell [44].

4. Wind-to-hydrogen

In the US, the NREL is overseeing the testing of a pilot-scale experimental wind-to-hydrogen energy production system [45]. The system links 100 K wind turbines with PEM-type and alkaline electrolyzers with the combined output of 20 kg/day of hydrogen (which is compressed to about 230 atm and stored in advanced storage tanks). The actual cost of the hydrogen produced is $5.50/kg, but it is projected to drop as larger and more advanced wind turbines are developed and installed. The cost target is $3.10/kg by 2012 and $2/kg by 2017. Electricity-generated hydrogen may become competitive with gasoline as and when the cost of wind power drops to $0.015/kWh.

Wind-to-hydrogen systems are being explored elsewhere as well [14,46], with different strategies to minimize costs. For example Takahashi et al. [46] have employed a variable speed wind generator and an electrolyzer installed in parallel with it for hydrogen production. Output power from the wind generator is smoothed and supplied to the power system as well as to the electrolyzer based on a cooperative control method.

5. Other routes to renewable hydrogen

Some experts propose hydroelectric, geothermal, and OTEC power as sources of renewable 'carbon-free' hydrogen. According to some estimates, 15 GW of new geothermal capacity will be developed over the next decade. Iceland and Hawaii could potentially build their hydrogen economies based to a large extent on geothermal energy. The outlook for this technology depends on three factors: resource availability, reducing costs, and technology improvement. U.S. DOE's Geothermal Technologies Center estimates that new geothermal plants are expected to operate at costs in the range of 4–6 cents/kWh. As for OTEC (ocean thermal energy conversion), the technoeconomic analysis suggests that the cost of electrical energy produced by an OTEC plant would be between a half and one-third of that of PV electricity [47]. Intensive efforts are also being made to generate hydrogen from anaerobic digestion of biomass [44,48,49] and biowastes [50]. But, as of now, success hasn't been achieved even in making the much older technology of methane production from biomass economically feasible [53,64]. How long it may take to generate hydrogen in a cost-effective manner from biomass can only be guessed. Moreover, none of these power sources are really 'carbon free' [51–53] and in some situations not only generate as much greenhouse gas emissions as coal-based power plants but a similar scale of other adverse environmental impacts as well [54–59,65]. Quite often there is a 'domino effect' of impacts; one impact becoming the trigger of another impact which in turn, may precipitate yet another impact, and so on [57,60,61,66]. Hence too much hope should not be pinned on them.

6. Economics of renewable hydrogen

The approximate costs of producing hydrogen with renewable and conventional energy sources are presented in Table 6. Cost of production of gasoline is also given for the sake of comparison. It can be seen that as of now production of 'renewable' hydrogen (for example from wind-electrolysis and biomass routes) is prohibitively costly.

The results of a cost analysis applicable to USA [62] have indicated that the electricity costs have a major impact on the hydrogen price if it is produced electrolytically. To produce hydrogen using electricity from solar or wind energy source (in order to have it 'carbon free') the electricity cost must be four times lesser than commercial electricity prices if the cost of hydrogen is to be made competitive with gasoline. The implication of this analysis is that several system improvements need to be made to reduce the cost of renewable hydrogen production.

For photovoltaic (solar) power to become competitive with the conventional electricity generation technologies the module cost has to drop to below a third of its present cost. The National Research Council (NRC), USA, has estimated that the cost to produce hydrogen via PV electrolysis today would be \$28.19/kg H_2 (at the installed cost of \$3.28/Wp and electricity cost of \$0.32/kWh). The NRC [63] has projected that assuming the installed capital cost of PV-electrolysis (for the future technology case) and solar electricity cost of \$0.098/kWh, the cost of hydrogen production would be \$6.18/kg H_2. While electricity at about \$0.1/kWh from the PV-electrolysis system looks quite attractive (especially for a distributed application), the cost of hydrogen production seems to be on the higher side. It is being hoped that technological developments may improve the economic competitiveness of the solar PV technology and reduce the cost of solar hydrogen. Attempts are on to explore dye-sensitized solar cells (known as Gratzel cells), the integration of organic and inorganic nanostructures into hybrid solar cells, etc. Photoelectrochemical cells for direct conversion of solar energy to hydrogen using semiconductor materials is another active area of research, but there is a long way to go before commercial success is achieved.

When integrating renewable energy production systems with hydrogen generation systems, it would be necessary that system components from different manufacturers be configured to function smoothly together. Until standardized systems with matched system components are developed, systems integrators will have to determine appropriate component sizes to meet the needs of electrolysis-based energy storage projects on a case-by-case basis. According to Harrison et al. [45], development of optimized power electronics packages that can maximize energy transfer, improve overall system efficiency, reduce system complexity, and lower capital costs are imperatives for systems-level improvements.

Table 6
Estimated cost of hydrogen production by conventional and 'renewable' routes.

Route	Cost[a] of hydrogen production
Natural gas reforming	1.03
Natural gas + CO_2 capture	1.22
Coal gasification	0.96
Coal + CO_2 capture	1.03
Wind electrolysis	6.64
Biomass gasification	4.63
Biomass pyrolysis	3.8
Nuclear thermal splitting of water	1.63
Gasoline (for reference)	0.93[b]

[a] In US dollar per kg; 2003 value.
[b] Per gallon (refined).

7. Conclusion

In summary, even as the use of 'renewable' hydrogen in place of fossil fuels appears to be the best way to halt global warming, and despite very strong efforts being done world-wide to make renewable hydrogen cost-effective, none of the available technologies are anywhere near economic viability.

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